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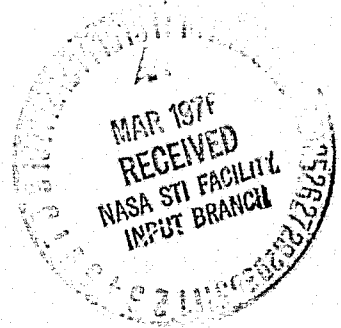
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A PRELIMINARY DISCUSSION OF GRAVITATIONAL PHYSICS EXPERIMENTS FOR THE SPACELAB ERA

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February 5, 1976



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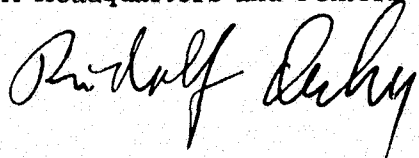
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16. ABSTRACT An overview of past, present, and proposed future experiments in gravitational physics is given. These experiments are concerned with the measurement of relativistic gravity effects to test theories of gravitation. Certain experiments which could be performed on Shuttle and Spacelab missions and the potential of Spacelab for gravitational physics research are discussed.					
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A PRELIMINARY DISCUSSION OF GRAVITATIONAL PHYSICS EXPERIMENTS FOR THE SPACELAB ERA

I. INTRODUCTION

The material in this report has been assembled to provide some general background information for planning and development of space flight missions. No attempt has been made to provide an in-depth analysis or scientific assessment of the subject. The authors realize that this cursory approach does not provide a complete and satisfactory treatment of the material from a scientific viewpoint. The purpose of this report is to stimulate specific studies concerned with the utilization of Spacelab for gravitational physics research.

It is anticipated that Spacelab and Space Shuttle missions will offer unique opportunities to perform gravitational and cosmology-related experiments in Earth orbit. The term gravitational physics is used to define research concerned with post-Newtonian or relativistic theories of gravitation (e.g., Einstein's General Relativity Theory). Certain cosmology-related observations which normally are not covered by planning efforts in the field of astronomy and astrophysics are also included in this category of experiments.

While gravitational physics is a very active research field, little effort has been expended thus far to investigate the potential of Spacelab for this important area of research. During 1972 and 1973, a Marshall Space Flight Center (MSFC) study group with participation from U.S. and European scientists investigated potential future space flight experiments and missions for gravitational research. This effort was focused mainly on interplanetary missions and automated spacecrafts in Earth orbit. In the spring of 1973, the Relativity Subpanel of the Astronomy Working Group (Space Shuttle program) generated a list of ideas for future gravitational physics experiments, and some consideration was given to the possible use of Space Shuttle. A Relativity Science Committee was established in the summer of 1974 to advise NASA Headquarters in planning future experiments and missions concerned with gravitational physics. The final recommendation of the committee should be available early in 1976.

II. SCIENCE BACKGROUND

Gravitation is a major force in the universe, but our knowledge of gravitation is rather limited. Newton's theory of gravitation, while remarkably successful in application to the solar system, is not adequate to describe many of the more recent discoveries in astronomy and astrophysics, including pulsars, quasars, x-ray sources, and the possible existence of black holes. Newton's theory is correct only for weak gravitational fields. The theory breaks down in strong gravitational fields associated with large masses and dense objects and with mass distribution over intergalactic distances.

Gravitation is a weak force in comparison with interactions inside the atom and nucleus. However, with increasing distance of interaction, gravitational forces become more important; over stellar and galactic distances, gravitation plays a dominant role. A relativistic theory of gravitation is needed to describe and model many astrophysical phenomena, to explain gravitational radiation, and for cosmology research concerned with the evolution and structure of the universe.

In 1916, Einstein published his General Relativity Theory which is a theory of gravitation, space, and time. Since then several other relativistic theories of gravitation have been published. Of these post-Newtonian theories, Einstein's General Relativity Theory seems to be the most complete theory at the present time. However, the experimental basis of General Relativity is weak, and experimental evidence is insufficient to determine whether Einstein's General Relativity Theory or one of the later developed gravitational theories is the best theory of gravitation. Presently, the scalar-tensor theory developed by Brans and Dicke in 1961 is the closest competitor to Einstein's Theory.

General Relativity Theory and other relativistic theories of gravitation predict a variety of phenomena which cannot be explained by Newton's theory. Einstein proposed three tests to check his theory: (1) the bending of light in the gravitational field of the Sun, (2) the gravitational redshift, and (3) the precession of the perihelion of planet Mercury. Actually, the gravitational redshift is not a test of General Relativity Theory but a test of the equivalence principle which is the foundation of General Relativity Theory as well as many other theories. The previously observed and unexplained precession of the Mercury perihelion (43" per century) agreed very well with Einstein's predictions. The bending of starlight measured during solar eclipses suffers from atmospheric effects and while measurements seemed to confirm Einstein's prediction, the

accuracy was not sufficient to give a final answer. The measurement of the gravitational redshift in the spectral lines of the Sun was even less accurate because of the turbulent conditions of the solar plasma.

No other important area of science rests on such a weak experimental basis as the field of gravitational physics. This situation is mainly the result of the extremely small magnitude of relativistic gravitational phenomena available to us in the solar system. The masses of the bodies in the solar system (including the Sun) are rather small compared to other objects in the universe. Consequently, solar system experiments and observations are limited by weak gravitational fields. In many equations describing gravitational effects, such as the deflection and the time delay of electromagnetic waves in the gravitational field, a term ϕ/c^2 determines the magnitude of the observable effect where ϕ is the gravity potential and c is the velocity of light. This term ϕ/c^2 is very small in the solar system, about 10^{-6} at the surface of the Sun and 10^{-9} for the surface of the Earth. Gravitational experiments, therefore, have to measure extremely small quantities with high accuracy. There are several reasons for the high accuracy requirements. Quite often theoretical predictions of gravitational effects from different theories differ only slightly. For example, the maximum light deflection near the Sun is approximately 1.75" according to General Relativity Theory and approximately 1.6" for the Brans-Dicke Theory. Very precise measurements are required to distinguish between competing theories and to determine to what degree experimental effects are described by theory.

Tests of fundamental concepts such as the equivalence principle should be performed to every possible degree of precision in the search for higher order deviations from the anticipated or predicted behavior. The history of science has shown that an essential increase in experimental accuracy has often revealed new effects and phenomena.

While most gravitational experiments are concerned with the measurement of extremely small quantities, their results are of great importance for our understanding of gravity and for increasing our information concerning the evolution, structure, and dynamics of the universe. The same phenomena, barely detectable in our solar system, can be the dominant factor in explaining many objects and events in the universe on a cosmological scale.

With recent advancements in instrumentation and technology, the small gravitational effects become more accessible to measurements. New tests of gravitational theories were proposed: the relativistic precession of a gyroscope

(by Schiff, 1960) and the time delay of radar signals passing close to the Sun (by Shapiro, 1964). Development of the Brans-Dicke Theory (1961) as a close competitor to Einstein's Theory, discovery of new and exciting objects and phenomena in astrophysics and astronomy, the serious search for gravity waves (by Weber), and the advent of space flight all initiated a strong interest and a variety of research activities in experimental relativity and gravitational physics in general.

A theoretical scheme called the Parameterized Post Newtonian (PPN) framework was developed to compare and analyze the various proposed gravitational theories and to develop criteria for experimental checks of theories. A set of parameters is used to describe the characteristics of each theory. In general these parameters have different values for different theories. For example, the parameter γ is a measure of curvature of space in the vicinity of a mass and can be determined by measuring the bending of light. In General Relativity Theory, $\gamma = 1$; in the Brans-Dicke Theory, $\gamma = (1 + \omega) / (2 + \omega)$ where ω is an adjustable coupling constant equal to approximately 5. In connection with the development of the PPN formalism, new experimental tests of gravitational theories were conceived (e.g., the Nordtvedt Effect). Most of these "new" effects, however, are orders of magnitude smaller than those known before and are beyond present and near future capabilities in instrumentation and technology.

In the following sections, a very brief summary of on-going and proposed research in gravitational physics is given first. This is followed by simplified descriptions of potential candidate experiments for Shuttle missions. Some of the experiments discussed have been proposed for orbital flight missions. In other cases, only the basic ideas have been developed; details of implementation do not exist. Careful studies are necessary to evaluate the feasibility and scientific merits of performing a particular experiment during Shuttle missions. Since the purpose of this document is to stimulate such studies, a variety of experiment ideas have been included without too much concern for actual feasibility at the present time. Scientific objectives and the nature of implementation required for a particular experiment are outlined in the descriptions. The results of the recommended studies will provide information needed to start mission planning.

III. ON-GOING AND PLANNED RESEARCH

A brief summary of on-going and planned experimental research in gravitational physics is given in this section. While the scope of this report is limited to Earth orbit experiments, a short discussion of ground-based and interplanetary experiments will provide a general background in this field.

In general, experiment objectives can be arranged in the following categories:

- a. Measurements of relativistic gravitational effects to test theories of gravitation.
- b. Tests of fundamental principles on which gravitational theories are based (e.g., Equivalence Principle).
- c. Cosmology-related observations (e.g., blackbody radiation in the universe).
- d. Detection and measurement of gravitational radiation.
- e. Measurements of fundamental constants.

A variety of experiments involving different phenomena of physics have to be performed to learn all aspects of gravitation and to compare predictions made by different theories. From the viewpoint of the PPN formalism, the same parameters can be determined by performing essentially different experiments. For instance, the parameter γ can be obtained by measuring the deflection of light or by measuring the geodetic gyroscope precession. However, the two experiments employ essentially different phenomena of physics: in the first case the interaction of electromagnetic waves or photons with the gravity field, and in the second case the interaction of a spinning mass with the gravity field. The two experiments are therefore different from the viewpoint of physics, and one cannot replace the other; but one complements the other. Attainment of similar values for γ in different ways will add to the confidence of the measurements.

Recent and on-going experimental research in gravitational physics is summarized in Table 1 and the Appendix. The research activities are divided into ground-based and space flight experiments. Experiments with a potential

TABLE 1. SUMMARY OF PRESENT AND FUTURE RESEARCH
IN GRAVITATIONAL PHYSICS

Measurement	Ground-Based	Space Flight	Parameter Measured
Deflection of Light/ Microwave	Solar Eclipses Hill Telescope Radio Astronomy Inter-ferometer	Earth Orbit Satellite	γ
Time Delay	Interplanetary Radar	Interplanetary Spacecraft (Mariner)	γ
Solar Oblateness Solar Quadrupole Moment	Dicke Telescope Hill Telescope		J_2
	Interplanetary Radar	Heliocentric Spacecraft	
Gyroscope Experiment a. Geodetic Precession b. Frame Dragging		Earth Orbit Satellite	γ Δ_1 Δ_2
Perihelion Precession	Mercury Observation Planetary Radar/Orbit	Heliocentric Spacecraft Mercury Orbiter	J_2 β γ

TABLE 1. (Concluded)

Measurement	Ground-Based	Space Flight	Parameter Measured
Gravitational Redshift (Equivalence Principle)	Pound Experiment	Maser Clock Space Probe	α
Eötvös Experiment (Equivalence Principle)	Dicke Torsion Balance Braginsky Torsion Balance	Earth Orbit Satellite	η
Blackbody Radiation a. Spectrum b. Isotropy	Microwave Radiometer Balloon Flight	Earth Orbit Satellite	
Time Change of G	Planetary Radar Lunar Observation	Spacecraft Tracking	\dot{G}/G
Gravitational Waves	Bar Antennas	Earth Orbit Interferometer and Bar Antennas	
Lunar Retroreflector Ranging	Laser Tracking		γ β Δ_1 Δ_2 β_2

application to Spacelab are discussed in more detail in Section IV. The remainder of this section is devoted to several on-going and proposed research projects.

A. Planetary Radar

Planetary radar is being used by I. I. Shapiro at Massachusetts Institute of Technology (MIT) to measure several gravitational effects. Radar signals transmitted from the Earth and reflected at the surface of the planets Mercury, Venus, or Mars provide a measurement of the relativistic time delay as well as orbit information from which various gravitational effects may be determined; for example, the change of the gravitational constant with time (\dot{G}), the precession of the perihelion, and the oblateness of the Sun. The measured round-trip time of a radar signal traveling between Earth and a planet increases as the signal path moves closer to the Sun; i. e., when the signal passes through a stronger gravitational field (relativistic time delay).

The oblateness of the Sun and the perihelion precession of Mercury are closely related. The Brans-Dicke Theory claims that a portion of the perihelion precession is caused by the oblateness of the Sun, a different interpretation from that given by Einstein's Theory.

Planetary radar experiments have been carried out for several years and will continue in the future. The accuracy of measuring results has improved over the years. So far, measurements have not yet been accurate enough to distinguish clearly between the Einstein and Brans-Dicke Theory. The main sources of error include solar corona effects on radio signal propagation and the topography of planets. Solar corona effects can be reduced by increasing the frequency of transmitted signals. There are indications that planetary topography can be determined by continuous measurements and collecting data over a period of several years. It seems possible that accuracy of relativistic measurements from planetary radar will further improve during coming years.

B. Radio Interferometry

Medium and long baseline radio interferometers have been used by several groups to measure the "light deflection effects" with microwaves (Sramek, Weiler, Counselman, Shapiro and others). Microwave radiation from two celestial radio sources (3C279 and 3C273) is used to measure the angular separation of the two sources. These measurements have been performed

during solar occultation of 3C279, which occurs each October. As the Sun's position in the sky approaches the two sources, the apparent angular distance between the two sources changes because of the deflection of microwaves in the gravity field of the Sun. Atmospheric fluctuations and the solar corona, both of which affect the microwave propagation, are the major error sources. From these observations radio astronomers have been able to measure the coefficient $(1 + \gamma)/2$. Dual-frequency techniques, whereby coronal bending (which depends on the frequency) is separated from gravitational bending (which does not), improve the accuracy of these experiments.

Precise measurements of γ will ultimately resolve the scalar-tensor versus general relativity issue. The most recent results reported by Sramek and others clearly favor general relativity. Their experiment used a 35 km baseline radio interferometer to study three nearly collinear radio sources at two frequencies and found the bending to be 1.015 ± 0.011 times that predicted by general relativity. The Brans-Dicke prediction differs by approximately 7 percent.

Shapiro, et al., have recently performed very long baseline interferometry (VLBI) measurements. They used two antennas at Greenbank and two antennas at Jyväskylä approximately 845 km distant to form two long baseline interferometers, one directed at 3C273 and the other simultaneously at 3C279. A gravitational deflection of 0.99 ± 0.03 times the Einstein prediction was reported. Efforts to improve the accuracy of these measurements are continuing to achieve results that will support either the Einstein or the Brans-Dicke Theory.

C. Lunar Laser Ranging

Three corner reflector arrays placed on the moon during the Apollo missions 11, 14, and 15 form a large triangle, approximately 1000 km on a side, on the lunar surface. Pulses of light from ruby lasers have been directed toward these arrays, and the time for the round trip is a measure of the distance to the Moon. The complex angular motions of the Moon about its center of mass can be determined with high accuracy from the range changes. The basic quantity measured by the lunar ranging experiment is the optical transit time to the reflectors and back. This is then expressed in length units. Lunar ranging gives the distance from the laser source to the retroreflectors to within 15 cm.

In addition, the potential exists to use lunar range data to check gravitational theory. A relativistic time-dependent moon motion correction term with an amplitude of approximately 1 m should be measurable. The Einstein Theory and the Brans-Dicke Theory with $\omega = 5$ give a difference in amplitude for this term of approximately 1 cm.

A term that has become known as the Nordtvedt Effect can also be checked through lunar ranging. This effect is a possible difference between the gravitational mass and the inertial mass of a large body. Einstein's Theory gives the ratio of the two masses as unity; other theories differ. The Nordtvedt Effect questions whether the gravitational self-energy of the body enters in the same way for both types of mass. If the gravitational self-energy does not contribute at all to the gravitational mass, the scalar-tensor theory with $\omega = 5$ gives a term of approximately 3 m in amplitude in the Earth-Moon distance. Experimental separation of Nordtvedt's term seems feasible. Thus, the equality of gravitational and inertial mass for the Earth can apparently be checked by lunar ranging.

A third way in which a departure from Einstein's Gravitational Theory would affect the motion of the moon has been discussed by Dicke. The scalar-tensor theory with $\omega = 5$ predicts a decrease of approximately 10^{-12} per year in G . This would lead to a secular deceleration of the lunar motion and an increase in the Earth-Moon distance. In principle, the secular deceleration of the Moon could be determined very accurately from the lunar range measurements over a period of several years, but separation of this effect from deceleration due to tidal influence could prove to be quite difficult.

D. Interplanetary Spacecraft Tracking

Several measurements of the relativistic time delay have been performed by Jet Propulsion Laboratory (JPL) in connection with interplanetary spacecraft missions (e.g., Mariner). The experiment is similar to the radar experiments previously mentioned. The main difference is the use of the spacecraft radio transponder for retransmission of the signal. The round-trip time of the radio signal between ground station and spacecraft is measured during superior conjunction of the spacecraft to determine the relativistic time delay as the signal path approaches the Sun. Again, the solar corona is a major error source. Another error source is some uncertainty in the spacecraft position as a result of random acceleration acting on the spacecraft.

E. Maser Clock Redshift Experiment

A space flight experiment to test the Equivalence Principle by measuring the gravitational redshift has been designated GP-A (Gravitational Probe A) and is scheduled for 1976. The Equivalence Principle asserts that there is no way of distinguishing locally between a gravitational acceleration and an oppositely directed mechanical acceleration. Einstein took this postulate as the cornerstone for his General Relativity Theory. The Smithsonian Astrophysical Observatory is providing the masers for the experiment and is responsible for the scientific part of the mission. In this experiment a frequency comparison is made between two very stable hydrogen maser clocks, one carried up and down through the Earth's gravitational field by a Scout rocket and one remaining on the Earth's surface. This comparison yields a gravitational frequency shift (redshift effect). According to Einstein's theory, the clock removed from the Earth will appear to run faster. After correction for first and second Doppler shifts, the change in clock rate will be determined as a function of gravitational potential. An accuracy of 50×10^{-6} in the measurement of the redshift is expected.

A ground-based experiment to determine the gravitational redshift was performed by Pound and Snider in 1964. They measured the change of gamma-ray energy over a vertical distance of 23 m (75 ft) utilizing the Mössbauer effect. The outcome of the experiment agreed within 1 percent with the value predicted by the Equivalence Principle.

F. Gyroscope Experiment

A space flight experiment to measure the relativistic precession of gyroscopes in Earth orbit is under development at Stanford University and MSFC. The experiment will require an automated spacecraft. A flight mission is envisioned early in the 1980's and is usually referred to as the gyro relativity experiment GP-B (Gravitational Probe B).

GP-B is designed to check two relativistic effects predicted by Schiff for the precession of a gyroscope in motion about a large massive body such as the Earth. The larger of the two effects, the geodetic effect, is due to the motion of the gyroscope about the Earth. The other effect is due to the Earth's rotation. To detect these effects, the spin axis precession of an extremely stable cryogenic gyro is measured using a Superconducting Quantum Interference Device (SQUID) magnetometer. The precession of the gyro is compared very accurately with the axis of a reference telescope pointing at a fixed star. The entire experiment package is enclosed in a liquid helium dewar operating at 1.4 K.

For a polar orbit around the Earth, the two effects occur at right angles. In Einstein's Theory they are, respectively, $6.9''/\text{year}$ and $0.05''/\text{year}$. Since the scalar-tensor theory predicts $6.3''/\text{year}$ for the geodetic effect, an experiment with an accuracy of $0.1''/\text{year}$ would provide a clear test between the two theories. The more challenging goal of the experiment, however, is to measure the smaller relativistic effect. To obtain such a measurement with an accuracy of 2 percent, a gyroscope with residual errors from extraneous sources of less than $0.001''/\text{year}$ is required.

The instrumentation and technology developed for the gyro relativity experiment can be applied to several other experiments. For example, the helium dewar/telescope concept could be used to measure the blackbody radiation in the universe. Another possibility is that a high Q bar antenna for gravitational waves could be mounted inside the dewar with a Josephson junction detector to measure the oscillations of the bar.

G. Counter-Orbiting Satellite Experiment

Lense and Thirring calculated from General Relativity Theory that a satellite in orbit around a massive body would experience a nodal dragging effect. Everitt and van Patten at Stanford University proposed to measure this effect with two counter-orbiting, drag-free polar satellites. The advance in the right ascension of the nodes would be measured by precision ground tracking and satellite-to-satellite Doppler ranging when the satellites pass each other near the poles. The experiment would provide a measurement of the frame dragging effect.

H. Heliocentric Relativity Satellite

A joint ESRO/NASA study for a future heliocentric relativity satellite (SOREL) was completed in 1973. Objectives of the study included measurements of the relativistic time delay using laser and radio systems and accurate orbit determination by radio tracking to measure the quadrupole moment of the Sun and perihelion precession. The satellite would be equipped with a control system to compensate for random acceleration forces to a level of 10^{-12} m/s^2 . An alternate mission to SOREL, a Mercury Orbiter with combined objectives of planetary exploration and gravitational research, is under consideration. By anchoring the spacecraft to the planet, the effect of random acceleration forces will be reduced drastically, and a high accuracy drag-free control system would not be required. Radio tracking (and possibly laser tracking) of the Mercury Orbiter would provide very accurate measurements of the perihelion precession, the solar quadrupole moment, and the relativistic time delay.

I. Other Ground-Based Experiments

A variety of gravitational experiments have been performed on or from the ground. The gravitational redshift effect was measured by Pound and Snider using gamma rays from an Fe^{57} source. The redshift was detected through resonance absorption employing the Mössbauer effect. A gravitational experiment involving the interactions of neutrons with the Earth's gravity field has been carried out recently. The experiment utilizes the wave nature of neutrons. A neutron beam is split into two beams travelling at slightly different gravity potential. The two beams are then compared in a neutron interferometer which measures the quantum mechanical phase shift caused by the difference of gravitational acceleration experienced by the two beams.

Other ground-based experiments which will be discussed in more detail in the next section include:

1. Measurement of isotropy and spectrum of the background blackbody radiation of the universe
2. Search for gravity waves
3. Eötvös-type experiments
4. Optical measurement of solar oblateness
5. Optical measurement of light deflection

These experiments could be considered as possible candidates for Shuttle and Spacelab missions. In some cases, proposals for space flight experiments have been made. In other cases, investigations are needed to assess their potential for implementation as Spacelab experiments.

IV. CANDIDATE EXPERIMENTS FOR SPACELAB

A. Cosmology

The discovery of the cosmic microwave radiation background in 1965 was subsequently identified with the primeval fireball in which the universe originated. This discovery by radio astronomers at Bell Laboratories has provided the most important support to the big bang theory to date. The

observational fact of cosmology is that the universe is expanding according to a remarkably simple law discovered by observing redshifts in the spectra of distant galaxies. The expansion has now cooled the fireball to a few degrees Kelvin. Accurate measurement of this temperature and determination of the isotropical nature of the radiation now becomes of great interest to cosmologists.

There are two primary limitations on radio telescopes that have made it impossible to measure the background spectrum to the accuracy required. Radio telescopes are not well suited to making absolute measurements of an isotropic background. Also, radio telescopes work efficiently only at wavelengths greater than the peak of the observed spectrum which seems to follow an approximately 3 K blackbody curve. The Earth's atmosphere begins to interfere with observations at wavelengths below 3 cm, just where the intensity of a 3 K blackbody reaches a maximum. To overcome these difficulties, special radiometers have been designed and built for balloon operation at high altitudes to get above some of the atmosphere. Measurements by several observers over a wide range of wavelengths have resulted in general agreement on a background temperature of 2.7 K; however, early balloon-borne experiments showed a departure from the 2.7 K curve at a wavelength of 0.1 cm. In fact, the observed radiation intensity at this higher altitude corresponds to approximately 8 K.

The background radiation has been found to be remarkably isotropic on a large scale through extensive ground-based observations, in agreement with the predictions of the primeval fireball hypothesis and in opposition to the steady state theory of the universe.

It is possible that most of the helium, deuterium, and lithium 7 we now observe were manufactured within approximately the first 100 s following the big bang by thermonuclear processes. The calculation of the resulting helium abundances, for instance, requires knowledge of the expansion rate at that time and also of the influence of irregularities and of particle horizons, and so depends essentially on gravitation theory. Using general relativity, a primordial helium abundance of approximately 27 percent by mass has been calculated. The scalar-tensor theory of relativity, due to Brans and Dicke, allows either more than 30 percent or 0 percent helium by mass. A primordial abundance higher than 30 percent has been ruled out by measurements of solar helium abundance. Dicke has proposed that the early expansion of the universe took place much faster than predicted by general relativity, and thus helium production reactions did not have time to run to equilibrium. Some comparative insights between general relativity and scalar-tensor relativity may result from further investigations.

Experimentation on Spacelab would afford the attractive opportunity to eliminate atmospheric interference, and thus a more precise determination of the intensity and isotropy of the background radiation can be established. Very significant improvements in sensitivity and resolution would be realizable with large radio telescopes in Earth orbit.

B. Gravitational Radiation

Gravitational waves are an interesting consequence of Einstein's General Theory of Relativity. This theory predicts that accelerated masses radiate gravitational fields propagating with the speed of light. Such gravitational waves resemble electromagnetic waves in that they carry energy, momentum, and information. However, gravitational waves react with all forms of matter-energy, whereas electromagnetic waves interact only with electric charges and currents. The first task of any experiment is to show that these waves indeed exist in nature. Great experimental ingenuity is required to detect gravitational waves, and claims by Weber that he has done so are now being checked by several investigators.

Astrophysical sources of gravitational waves could take the form of a star pulsating and rotating wildly, a collapsing star, an exploding star, or a chaotic system of many stars. Bursts of gravitational waves could also stem from debris falling into a black hole, collisions between black holes, or supernova explosions.

Weber has shown that a gravitational wave propagating through a material body will induce a time-varying strain, forcing the body into oscillation. Early detectors were designed to measure the resonant mass quadrupole due to gravitational influence. Radiation incident normally to the cylinder axis of massive aluminum cylinders would excite the longitudinal compressional mode of the cylinder corresponding to the fluctuations in distance between two test particles as predicted by general relativity. Weber used a 1.5 ton bar of aluminum, approximately 150 cm long and 60 cm in diameter, suspended by a sling of piano wire about its center, and hung from acoustical filters in a vacuum to monitor the frequency of strain. Another of Weber's experimental detectors takes the form of a large aluminum disk antenna. The radial mode of the disk would not be excited by quadrupole radiation incident along the axis, but there would be a response to any scalar radiation supporting the theory due to Brans and Dicke. Tests conducted so far with this apparatus indicate that an improvement in sensitivity is required before any meaningful conclusions can be made in support of one theory over another.

Several other investigators are experimenting with variations of Weber's devices, and recently cryogenic refinements are being applied to such systems. Hamilton and Fairbank are preparing an experiment with a 5500 kg (12 000 lb), 0.9×3 m (3×10 ft) cylinder cooled to millidegree temperatures and suspended by superconducting magnets. Rather than the piezoelectric crystals used by Weber, Hamilton's apparatus will feature a new superconducting accelerometer to detect any bar motion. The entire experiment will be surrounded by a perfect superconducting shield to eliminate any excitation from electromagnetic radiation.

Other schemes to detect the extremely small motion due to gravitational radiation are being studied. Forward and Moss have developed a wide band receiver based on a Michelson interferometer with heterodyne detection of coherent light. In this antenna concept, the relative motion of loosely suspended masses in space is observed, and the ac phase shifts in the optical path due to relative ac displacement of the masses are measured interferometrically. Three satellites widely separated in the same orbit are controlled by slowly acting servomechanisms to keep their separation distances approximately equal and to maintain approximately a right angle between two laser links between the center satellite and the other two. The direction of gravitational wave propagation is such that the optical path along the line of propagation (reference path) is not affected, but an ac displacement is induced in the perpendicular (signal) path. The extreme sensitivity achievable by heterodyne ac phase detection makes the laser-linked antenna approach look promising. The discriminating features of this system overcome most of the noise problems, including light bending gravitational effects which are either negligible or can be calculated out of the ac gravitational wave measurements.

Weber has recently submitted a proposal to the PACE (Physics and Chemistry in Space Experiments) Working Group to fly a new gravitational wave detector on Shuttle. The proposed detector incorporates a large single crystal of sapphire operating near 0 K, resulting in a predicted increase in Q by many orders of magnitude. Operation in space has the advantage of avoiding disturbances due to the Earth environment and greatly reduces the requirements on a support system for the detector.

C. Eötvös-Type Experiments

The classical Eötvös experiment tests the weak equivalence principle by comparing the ratio of gravitational mass to inertial mass for different materials. It is an axiom of general relativity and virtually all other theories of gravitation

that this ratio, $K = M_g / M_i$, is a constant for all bodies, independent of their composition. This statement is called the Weak Equivalence Principle.

The evidence for this hypothesis consists primarily of experiments of the Eötvös type. Given two bodies, A and B, these experiments may be regarded as measurements of the Eötvös ratio:

$$\eta(A, B) = 2 \frac{K(A) - K(B)}{K(A) + K(B)} .$$

Experiments by Eötvös in 1890 yielded the conclusion that the difference of M_i / M_g for wood and platinum was $< 10^{-9}$. Eötvös used the gravitational force acting toward the Earth's center to produce a torque on two masses suspended from a torsion balance.

Dicke and the Princeton group incorporated several refinements into this experiment in 1964; e. g., they used the gravitational field of the Sun and the Earth's centripetal acceleration toward the Sun to produce the torque on the balance. This experiment using aluminum and gold resulted in the conclusion that the difference in acceleration for these two materials falling toward the Sun is at most one part in 10^{11} .

Braginsky and Panov claim an order of magnitude improvement over the Dicke group from their experiment in 1971 using platinum and aluminum.

Currently, there are two Eötvös-type experiments that have been proposed for Earth orbit, one by Chapman and Hanson and the other by Worden and Everitt.

Chapman and Hanson propose to take advantage of circular Earth orbital environment. Their apparatus consists of a spinning aluminum wheel with inertial angular velocity in the direction of the normal to the orbital plane. A sensitive accelerometer is mounted radially in the plane of the wheel. It contains two proof masses, one gold and one aluminum, suspended coaxially and independently by electrostatic forces. The main advantages of this system over a conventional rotational balance system are that it is relatively insensitive to gravity gradients and that it is possible to use a resonance effect to enhance the Eötvös effect.

Worden and Everitt propose tests of the equivalence of gravitational and inertial mass by employing cryogenic techniques. The experiment consists of monitoring the motion of two coaxial cylindrical test masses of different composition, and the apparatus is designed to take full advantage of the cryogenic environment. They point out that an orbital experiment offers the hope of improved accuracy for three reasons: (1) the driving acceleration is approximately three orders of magnitude larger, approximately 950 cm/s^2 compared with 0.6 cm/s^2 for the solar acceleration; (2) a space experiment is isolated from seismic vibration, which is a limiting factor for earth-bound experiments, and (3) an orbital experiment may be more easily arranged to avoid random gravity gradient effects due to the motion of large masses near the laboratory. For these reasons, orbital Eötvös-type experiments are expected to yield experimental values of η to higher accuracy than previous experiments. Further improvements in sensitivity may be achieved by cryogenic techniques. There is the obvious reduction in thermal noise and the ability to apply superconducting shields to eliminate external magnetic influences. Frictionless superconducting magnetic restraint and control of test masses can be achieved, and a very stable and sensitive position readout based on persistent currents and Josephson junctions or other superconducting magnetometers is possible. An additional advantage is that the thermal expansion of most materials approaches zero at cryogenic temperatures. There are also advantages in making the satellite experiment drag free.

The history of Eötvös-type experiments is given in Table 2.

D. Quadrupole Moment and Oblateness of the Sun

In the middle of the 19th century, it was discovered that the planet Mercury was apparently not behaving in accordance with Newtonian mechanics. An excess perihelion motion over the theoretical value was observed, creating a search for some extra perturbing mass in the solar system. No such mass was found, but the anomaly was apparently explained by Einstein's General Relativity Theory which predicted the excess motion of $43''$ per century. A perihelion advance of Mercury could be caused by a quadrupole moment of the Sun, as has been pointed out by Dicke. The Brans-Dicke Scalar Tensor Theory of Gravitation has generated new interest in the perihelion motion of Mercury in recent years. The quadrupole moment of the Sun's gravity field is described

TABLE 2. "EÖTVÖS" EXPERIMENTS

Investigators →	Eötvös	Dicke	Braginsky	Chapman/Hanson	Worden/ Everitt
When	1890, 1922	1963	1971	Future (Proposed)	Future (Proposed)
Scientific Organization		Princeton	Moscow State University	MIT	Stanford University
Instrument	Torsion balance	Torsion balance	Torsion balance	Orbiting coaxial cylinders	Orbiting coaxial cylinders
Test Materials	Wood and Pt	Au and Al	Pt and Al	Au and Al	Niobium and Al
Torquing source	Component of Earth gravity	Sun gravity	Sun gravity	Earth gravity	Earth gravity
Acceleration level (cm/s ²)	1.7	0.6	0.6	10 ³	10 ³
Accuracy claimed	10 ⁹	10 ¹¹	10 ¹²	10 ¹⁴	10 ¹⁵
Reasons for better accuracy than from previous experiments	Torsion balance concept	Periodic torquing	Oscillatory system with long relaxation time	Acceleration level high; no seismic disturbances	Same as Chapman's plus cryogenic techniques

by a dimensionless parameter J_2 which appears in the following expression for the Newtonian potential:

$$U(r) = \frac{M}{r} \left[1 - \left(\frac{J_2 R^2}{r^2} \right) P_2 \right] ,$$

where M and R are the mass and radius of the Sun and P_2 is the second Legendre polynomial.

A quadrupole moment could cause an optically oblate Sun. Dicke has measured and reported an oblateness of approximately 5×10^{-6} which is a difference in the equatorial radius (r_{eq}) and the polar radius (r_p) of the Sun according to the relationship $(r_{eq} - r_p)/r_{eq} = 5 \times 10^{-6}$. This oblateness amounts to a difference of approximately 35 km between equatorial and polar radius, or approximately $0.05''$ as seen from the Earth. According to the Brans-Dicke Theory (with $\omega \approx 5$), $39''$ of the $43''$ excess perihelion motion of Mercury can be explained. The remaining $4''$ would be caused by a quadrupole moment indicated by an oblateness of 5×10^{-6} as measured by Dicke. This interpretation has been criticized on the grounds that surfaces of constant pressure density, temperature, and gravity potential on the Sun do not necessarily coincide. Nevertheless, the experimental work of Dicke and the Princeton group is credited with important contributions to the state of knowledge in solar oblateness. They have refined techniques to observe the Sun's limb and from it to determine solar oblateness. The limb of the Sun is sharply defined, the transition from dark to bright taking place over approximately $0.1''$. The fundamental problem concerns observing the limb position to an accuracy of $0.005''$. Noise and anisotropic seeing conditions cause images to be slightly elliptical and spread, making determination of the brightness gradient extremely difficult. The challenge has been a formidable one.

The principle of the special telescope designed and built by the Dicke group to measure oblateness can be described briefly. The instrument incorporates an occulting disk slightly smaller than the solar image, permitting a ring of light to pass the disk. This light falls on a rapidly rotating wheel concentric with the occulting disk and having two unequal apertures. The disks are held to the center of the solar image by a servomechanism, and the scanning of the Sun's edge determines whether the light flux is uniformly distributed

about the occulting disk. Several clever schemes are employed in the instrument design and operational techniques to reduce errors to a minimum. The telescope and detection system can be regularly rotated to eliminate errors arising from an elliptical occulting disk, lens astigmatism, or other departures from axial symmetry. Techniques are employed to separate fluctuations in oblateness due to atmospheric parameters — temperature, pressure, humidity, and seasonal changes. In addition to making measurements in different color bands, different magnifications of the solar image can be used to eliminate ambiguous observations. Still, the observations of the solar oblateness have a degree of uncertainty attached to them; however, it is anticipated that more precise observations in the future (e.g., through the use of planetary radar or by experiments in space) will support or reject the idea of a solar quadrupole moment.

The telescope and peripheral apparatus developed by Hill to measure gravitational deflection of light is well suited for solar oblateness measurements. It also employs two slits located on the edge of the Sun, and these slits radially scan across the solar limb at the 1.6 Hz rate. For a given scanning amplitude the radial positions of the slits are servoed to the position where the second harmonics of the detectors, receiving light through the slits, are zero. A Fourier Coefficient Technique (FCT) for defining a point on the solar limb independent of the Earth's atmospheric seeing conditions has been developed by the Hill group, and this technique is the basis for their claimed improvement over previous measurements. Their measurements have shown the Sun to be much more spherical than indicated by Dicke's measurements — entirely consistent with a uniformly rotating body as exhibited by its visible surface. This would seem to support the theory that any quadrupole moment, if it does exist, must have its origin in some internal solar mechanism, or perhaps in a thermal gradient between the solar equator and the poles.

A space version of the ground-based experimental procedures could be conceived to take full advantage of the elimination of atmospheric effects. Quite possibly, a Spacelab oblateness experiment could be combined with a light-bending experiment as discussed in the next section. In addition to providing valuable information for relativity, the data from such an experiment could be significant to the solar investigators currently attempting to model the Sun.

A more accurate measurement of the quadrupole moment of the Sun would be obtained from the Mercury Orbiter mission mentioned earlier.

E. Deflection of Light in the Gravitational Field of the Sun

In 1916, Einstein published his famous General Theory of Relativity, and one aspect of this theory is that near the Sun, light is deflected as shown in Figure 1 and according to the relation

$$\alpha = \frac{4 GM}{c^2 r}$$

where α is the angle of deflection

G is the constant of gravitation

M is the mass of the Sun

r is the distance from the center of the Sun to the light ray

c is the speed of light in vacuum.

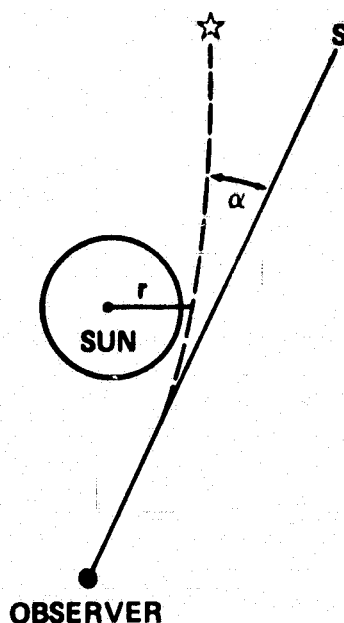


Figure 1. Light deflection (Einstein Effect).

Using the following values:

$$G = 6.67 \times 10^{-8} \text{ cm}^3 \text{ g}^{-1} \text{ s}^{-2}$$

$$M = 1.991 \times 10^{33} \text{ g}$$

$$c = 2.998 \times 10^{10} \text{ cm s}^{-1}$$

$$r = 6.956 \times 10^{10} \text{ cm} ,$$

we can calculate α at the Sun's limb to be $1.75''$. As we move out from the limb, α decreases along an hyperbola as shown in Figure 2. To verify this hyperbola dependence, it is necessary to observe the behavior of stars close to the Sun's limb where the deflection is the greatest. Quite often during an eclipse there have been an insufficient number of measurable stars near the limb. This stems from the fact that the Sun passes relatively few suitable stars in its yearly movement along the ecliptic, and the chances are remote that stars of the proper magnitude will be favorably positioned at the time of totality. Furthermore, these measurements have historically been plagued by poor weather and optical distortions due to temperature changes. Frequently total eclipses take place in jungles, in the middle of oceans, in deserts, or in arctic tundras, making it necessary to observe under less than optimum conditions. The Sun's corona is also a problem in making observations

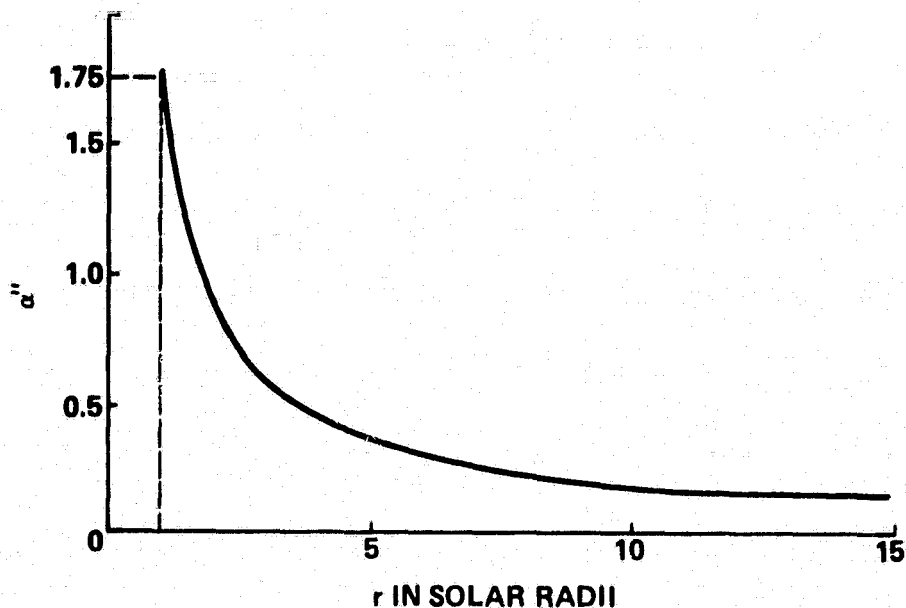


Figure 2. Light deflection near the Sun.

close to the limb since the contrast between the star and the background on the photographic plate is seriously reduced. The intensity of the corona further depends on the solar activity cycle. For these reasons, it will probably be impossible to ever measure the full $1.75''$ predicted by Einstein for light deflection at the Sun's limb. In fact, the interesting portion of the hyperbola of Figure 2 has hardly been covered by observations to date. In summary, light deflection measurements require the absolute determination of a very small quantity during the particular short time interval (7.5 minutes maximum) under the usually quite difficult conditions of a temporary field station in some more or less remote part of the world.

Fewer than 30 total solar eclipses have taken place since Einstein first published his theory in 1916. Most of these eclipses have been exploited to measure light deflection, but altogether there has been less than 100 minutes of observing time. Some of the early measurements still compare rather well with more recent results. The most recent experiment took place in Africa in 1973, but these measurements were plagued by atmospheric dust. For a rather complete discussion of observations over the years, see the Klüber paper.

Until quite recently, the only measurements of light deflection took place during total eclipses. The apparent position of a group of stars close to the Sun during an eclipse was later compared to the same group pattern of stars taken at night, with appropriate reference schemes employed to detect the absolute deflection. In the 1960's work was begun by Hill and others to design and construct instrumentation, including the development of a telescope to achieve an improved measurement of the gravitational deflection of light. The method employed is that of using a highly accurate measurement of the diameter of the Sun to establish a scale of distances on the sky, and measuring the separation between two stars as a function of time while the Sun appears to move on the celestial sphere; the experiment is carried out in full sunlight, obviating the necessity of waiting for a total eclipse of the Sun. Positions of the stars and the Sun are determined photoelectrically, and compensation for atmospheric refraction and dispersion, as well as changes in scale in the focal plane, is an integral part of the apparatus. An improvement of an order of magnitude in accuracy over prior measurements is expected.

Light deflection experiments carried out during eclipses have resulted in published values for the PPN parameter γ . The angular deflection at the limb can be expressed as

$$\alpha = 1.75 (1 + \gamma) / 2''$$

where Einstein's Theory gives a value of unity for γ . An uncertainty in the value of γ of 20 to 30 percent from optical measurements is generally accepted. It is believed that an experiment from Earth orbit could very significantly improve our confidence in an experimental value for γ and lend persuasive support for any gravitational theory predicting the value that is found. A relatively simple set of measurements could be carried out using a suitably configured telescope and means for occulting the Sun. This instrument could be used to study any apparent movement in the star pattern adjacent to the limb with and without the Sun present and to record this information on a photographic plate. Another possibility to be assessed would involve the employment of a vidicon camera or other such detector in an electronic system. Pointing accuracy and stability will be important to tests of this kind if arc-second deflections are to be detected with high accuracy.

F. Spacelab as a Development Facility

The Spacelab concept offers unique opportunities as a development and test laboratory for critical instrumentation required for certain gravitational experiments.

For example, in the low-gravity environment of Spacelab, low-gravity accelerometers and magnetic or electrostatic mass suspension systems could be tested to assess their performance limit with respect to noise, sensitivity, and long-term stability. The behavior of liquid and superfluid helium could be analyzed to obtain practical data for the design of liquid helium flight dewars. Development of liquid helium dewars for long-duration space missions is required not only for gravitational experiments but also for infrared astronomy and high energy physics experiments.

V. CONCLUSIONS AND RECOMMENDATIONS

Several advantages can be gained by performing gravitational experiments in Earth orbit. For example, space flight environment offers:

- a. Low acceleration

b. Low vibration

c. Elimination of the effect of Earth's atmosphere.

On the Earth's surface, the gravitational acceleration, seismic noise, and vibrations are limiting factors and major error sources in certain types of experiments. In cases where optical or microwave measurements are involved, the Earth's atmosphere can be a limiting element.

The Space Shuttle offers two essentially different modes of implementation for scientific experiments in space:

a. Experiments mounted and operated in the Spacelab during Sortie missions

b. Automated payloads put into orbit by the Shuttle only or by using an additional propulsion stage.

Another important feature of Shuttle is the ability to retrieve a payload for refurbishment and reuse. In general, Spacelab experiments will be less expensive than automated payloads because a number of support functions, including electrical power and data communication, are provided by the Spacelab systems. The mission duration, and therefore the experiment operation, is rather short for Sortie missions. The nominal mission duration is 7 days. However, extended missions up to 30 days are included in the planning. The duration of Sortie missions should be sufficient for some gravitational experiments. Experiments which require a longer operation time will need the automated payload approach.

Spacelab experiments offer the possibility of astronaut participation. Manned operation of experiments, including checkout, initial adjustment of equipment, and perhaps repair could be a major advantage for certain types of experiments. Another important possibility is the use of Spacelab for technology experiments; for example, to test instrumentation concepts requiring a low-g environment which is not available on the Earth's surface for extended periods of time.

Gravitational experiments requiring long observation time and/or extremely low-g and vibration-free environments have to be implemented as automated payloads. A propulsion stage, the Interim Upper Stage (IUS), and

later the Tug, are available to transport payloads from the lower Earth orbits of Shuttle to higher altitude orbits. The automated payloads would be self-contained satellites. The possibility of payload retrieval and return to Earth is available.

An extensive study effort has been under way for some time to define scientific payloads and experiments for early Shuttle missions, with first flights scheduled in 1980. Gravitational experiments must be introduced and included in mission planning and definition activities to have a chance for a place on an early Shuttle flight. Further study efforts should be initiated to fully identify candidate gravitational experiments and to define their instrumentation and mission requirements.

APPENDIX

IDENTIFICATION OF PARAMETERS IN TABLE 1

γ is a measure of the influence of mass on the curvature of space.

β is a measure of the nonlinearity due to the superposition of two gravitational fields.

The α 's (α_1 , α_2 , and α_3) show to what extent and in what manner the particular theory singles out a preferred universal rest frame.

The ζ 's (ζ_1 , ζ_2 , ζ_3 , and ζ_4) are conservation of momentum law parameters.

The above nine parameters are related to a revised system of parameters as follows:

$$\alpha_1 = 7\Delta_1 + \Delta_2 - 4\gamma - 4$$

$$\alpha_2 = \Delta_2 + \zeta - 1$$

$$\alpha_3 = 4\beta_1 - 2\gamma - 2 - \zeta$$

$$\zeta_1 = \zeta$$

$$\zeta_2 = 2\beta + 2\beta_2 - 3\gamma - 1$$

$$\zeta_3 = \beta_3 - 1$$

$$\zeta_4 = \beta_4 - \gamma$$

where,

β_1 is a measure of how much gravity is produced by unit kinetic energy.

β_2 is a measure of how much gravity is produced by unit gravitational potential energy.

β_3 is a measure of how much gravity is produced by unit internal energy.

β_4 is a measure of how much gravity is produced by unit pressure.

ζ is a measure of how much more gravity is produced by radial kinetic energy toward the observer than by transverse kinetic energy.

Δ_1 is a measure of how much inertial frame dragging is produced by unit momentum.

Δ_2 is a measure of how much easier it is for momentum to drag inertial frames radially toward the observer than in a transverse direction.

In addition to these parameterized post-Newtonian (PPN) parameters, other quantities shown in Table 1 are as follows:

J_2 is a nonrelativistic quantity and is a measure of the Sun's oblateness or quadrupole moment.

$$\eta(A, B) = 2[k(A) - k(B)] / [k(A) + k(B)]$$

where $k = m_p / m_i$ is the ratio of passive gravitational mass to inert mass for two material bodies A and B.

G is the gravitational constant.

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APPROVAL

A PRELIMINARY DISCUSSION OF GRAVITATIONAL PHYSICS EXPERIMENTS FOR THE SPACELAB ERA

By Rudolf Decher and Carl E. Winkler

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.



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